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# THE EFFECT OF HIP JOINT ANGLE ON ISOMETRIC MID-THIGH PULL KINETICS

*Original Research*

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## ABSTRACT

The aims of this study were to compare isometric mid-thigh pull (IMTP) peak force (PF), time-specific force values (100-, 150- and 200 ms), rate of force development (RFD) at pre-determined time bands (0-100, 0-150 and 0-200 ms) and net forces between two commonly adopted hip joint angles (145°[hip<sub>145</sub>] and 175°[hip<sub>175</sub>]) with a 145° standardised knee angle. Twenty-eight collegiate athletes (age: 21.7 ± 1.5 years, height: 1.75 ± 0.08 m, mass: 81.5 ± 8.4 kg) performed two IMTP trials at each hip joint angle in a randomised counterbalanced order. A subgroup (n=10) performed the IMTP testing seven days later to establish between-session reliability. Intraclass correlation coefficients (ICC) and coefficient of variation (CV) demonstrated high within-session reliability and acceptable variability for all IMTP kinetics at each posture (ICC ≥ 0.86, CV ≤ 13.7%) excluding hip<sub>175</sub> RFD 0-100 ms and net force at 100 ms which demonstrated greater variability (CV = 18.1-18.5%). High-between session reliability and acceptable variability were observed for all IMTP kinetics at each posture (ICC = 0.72-0.97, CV = 4.5-12.8%), excluding RFD 0-100 ms which demonstrated greater variability for both postures. Hip<sub>145</sub> produced significantly greater time-specific force values ( $p \leq 0.025$ ,  $g = 0.25$ -0.28), RFD at pre-determined time bands ( $p \leq 0.001$ ,  $g = 0.59$ -0.78) and net forces ( $p \leq 0.001$ ,  $g = 0.57$ -0.74) compared to hip<sub>175</sub>. Trivial non-significant differences were demonstrated between postures for PF and force at 100 ms ( $p > 0.05$ ,  $g \leq 0.14$ ). Significantly greater body weights (weighing period force) were observed with hip<sub>175</sub> compared to hip<sub>145</sub> ( $p < 0.001$ ,  $g = 0.74$ ). Coaches should consider administering a hip<sub>145</sub> for IMTP testing as greater IMTP kinetics and lower levels of pre-tension during the weighing period are achieved with this posture.

**Key words** rate of force development; time-specific force; peak force; net force; assessment

## INTRODUCTION

The neuromuscular qualities of the lower limb can be evaluated using force-time curves recorded from the isometric mid-thigh pull (IMTP). The IMTP is commonly used to assess the peak force (PF) production but a further advantage is the ability to inspect an athlete's ability to produce force (4, 12, 15, 22), rate of force development (RFD) (4, 12, 22) and impulse (8, 43) at critical time intervals. The IMTP has been shown to demonstrate high within- and between-session reliability measures for PF (8, 11, 14, 15, 22), time-specific force values (4, 12, 15, 22), rate of force development (12, 22) and impulse (8, 43) across different time intervals. Due to the high reliability and its simplicity to administer, the IMTP is commonly used to evaluate the force-time qualities to prescribe future training such as inspection of the dynamic strength index when combined with PF during a jump (45); while also used to monitor adaptations to training (3). Additionally, the IMTP can be used as a potentially safer surrogate to dynamic one repetition maximum (1RM) strength testing (8, 11), with strong correlations observed between IMTP PF and 1RM back squat ( $r \geq 0.96$ ) (33, 35), snatch and clean and jerk ( $r \geq 0.83$ ) (4) and deadlift ( $r = 0.88$ ) (11). Moreover, inspecting neuromuscular preparedness (18) and assessment of bilateral (1) and unilateral force production asymmetries (13) are further purposes of IMTP testing.

The IMTP is modelled on the start of the second pull position of the clean whereby the largest forces, velocities and power are generated (17, 23). However, a contentious issue in IMTP testing is the selection of appropriate knee and hip joint angles. Currently there is no agreed consensus on the appropriate knee and hip joint angles for IMTP testing. The IMTP was first introduced by Haff et al. (23) where knee and hip angles of  $144 \pm 5^\circ$  and  $145 \pm 3^\circ$  were reported, respectively. Since then, a diverse spectrum of knee angles ( $120$ - $145^\circ$ ) have been reported including fixed specific angles of  $130^\circ$  (33, 34) and  $140^\circ$  (9, 36, 38), while some researchers report a range of knee angles adopted by subjects including  $120$ - $130^\circ$  (10,

46),  $125 \pm 5^\circ$  (1),  $125-135^\circ$  (4),  $127-145^\circ$  (20, 21, 28),  $137.6 \pm 12.9^\circ$  (22),  $141 \pm 10$  (27) and  $140-145^\circ$  (40). Similarly, a wider range of hip joint angles have been reported within the literature ranging from flexed positions of  $124 \pm 11^\circ$ , resulting in a clear forward lean of the trunk, upright positions of  $140-145^\circ$  (8, 22, 38, 40) and more extended positions of  $155-165^\circ$  (39) and  $170-175^\circ$  (1, 4, 29, 42, 47). As such, these different knee and hip angles result in different body positions relative to the bar which could impact the force production capabilities during IMTP testing (Figure 1) (5, 6).

**\*\*Insert Figure 1 about here\*\***

Notably a large contingent of studies do not report their knee (12, 13, 30, 41, 43, 45) or hip joint angles (12, 13, 20, 21, 28, 30, 33, 34, 36, 37, 44, 45) for IMTP testing and simply describe the body positioning. For example, researchers have stated self-preferred position (12, 13, 43, 45), bar position below crease of hip (36), bar position at height of knee (30) (which is clearly not a mid-thigh pull, or the start of the second pull during a clean), upright trunk (10), near vertical trunk (40), shoulders placed over the bar (37) and flat trunk with shoulders in line with bar (46). Failure to provide hip and joint angles for IMTP testing makes determining and replicating IMTP protocols difficult. The inconsistencies in postures reported within the literature and failure to provide knee and joint angle data could result in discrepancies between studies; in particular the reliability and range of correlations with dynamic performance. Interestingly, some knee joint angles ( $127-145^\circ$ ) for IMTP testing were calculated during 2-dimensional analysis of each subject's actual weightlifting performance (20, 21), but hip joint angles were not provided. This method would require athletes firstly to be competent at the clean and would require extensive periods of time to collect and analyse such data, and would therefore be too time consuming and impractical for testing large squads of athletes and cohorts of subjects.

Differences in joint angles can impact force production due to changes in the length tension relationship in skeletal muscle, while the force produced acts through different moment arms (48). Consequently, this can influence the contractile properties influencing force (5, 6, 32) and RFD (32) production during isometric testing. Marcora and Miller (32) reported differences in PF and maximum RFD during the isometric leg press between knee angles 120° and 90°, respectively. Similarly, Beckham et al. (5) compared isometric PF in key positions of the conventional deadlift (floor, knee, mid-thigh pull, lockout) revealing the mid-thigh pull position (knee angle 125°, hip angle 145°) generated the highest PF, significantly higher than any other position. However, the authors failed to provide the knee and hip joint angles of the lockout position, thus it is uncertain whether the hip and joint angles adopted for the lockout position were reflective of commonly adopted IMTP hip and knee joint angles reported within the literature.

There is a paucity of research comparing IMTP kinetics between different knee and hip joint angles. Comfort et al. (8) compared IMTP kinetics between commonly reported knee (120°, 130°, 140°, and 150°) and hip angles (125° and 145°) and self-preferred posture reporting no meaningful or significant differences ( $p > 0.05$ ,  $d \leq 0.061$ ) in PF, maximal RFD or impulse at 100-, 200- and 300 ms across postures. Additionally, high between session-reliability was observed for all kinetic variables irrespective of posture. The authors advocated the use of a self-preferred mid-thigh pull position for IMTP testing due the high reliability and lack of differences with the other postures, with also the potential ability to speed up IMTP testing to a reduced learning effect. Contrary to the findings of Comfort et al. (8), Beckham et al. (6) has advocated a hip joint angle of approximately 145° for IMTP testing, reporting greater IMTP kinetics (PF and time-specific force values) compared to a flexed 125° hip joint angle (standardized 125° knee joint angle) with small to large effect sizes in athletes with weightlifting experience and small to moderate effect sizes without weightlifting experience.

As such, given the conflicting findings from these two studies, there is no consensus on the optimal joint angle for IMTP testing.

There is a requirement therefore, for further investigations into the effects of different joint angles on IMTP kinetics; specifically comparing the commonly reported and adopted hip angles of 145° (8, 22, 23, 38, 40) and 175° (1, 4, 29, 42, 47) within the literature; which Comfort et al. (8) and Beckham et al. (6) did not investigate. These two hip angles result in different body positions relative to the bar which could potentially effect force production during IMTP testing (Figure 1). Practitioners use the IMTP to assess the rapid force production properties of their athletes, thus it is imperative that athletes adopt the most optimal and favourable position (joint angle) to rapidly produce force. Subsequently, the results from this study should provide greater insight into which positions are favourable and optimal for isometric rapid force production. Thus, the aims of this study were to compare IMTP PF, time-specific force values, RFD at pre-determined time bands and net forces between two different hip joint angles (145° and 175°) with a standardised knee angle of 145°. It was hypothesised that greater IMTP kinetics would be observed with a 145° hip joint angle compared to a 175° angle, due to advantageous length tension relationships of the hip extensors.

## **METHODS**

### Experimental approach to the problem

A repeated measures, within-subjects design was used to evaluate the effects of hip joint angle (145° vs 175°) at a standardised knee joint angle (145°) on IMTP PF, time-specific force values, RFD at pre-determined time bands and net forces. A randomised and counterbalanced testing protocol was used to control for order effect whereby subjects performed two maximum effort IMTPs in each position while standing on a force plate

sampling at 1000 Hz. IMTP testing was performed on two separate testing sessions seven days apart at the aforementioned postures to determine the within-session and between-session reliability of each measure and to determine the effect of hip joint angles on the dependent variables (PF, time-specific force values, RFD at pre-determined time bands and net forces).

### Subjects

Twenty-eight (23 male and 5 female) collegiate athletes (age:  $21.7 \pm 1.5$  years, height:  $1.75 \pm 0.08$  m, mass:  $81.5 \pm 8.4$  kg, relative one repetition maximum power clean:  $1.06 \pm 0.18$  kg/BM) from rowing and soccer participated in this study. A subgroup ( $n=10$ ) returned on a second occasion seven days later at the same time of day to determine between-session reliability. Based on the work of Beckham et al. (5) for differences in isometric PF between postures, a minimum sample size of 15 was determined from an *a priori* power analysis using G\*Power (Version 3.1, University of Dusseldorf, Germany) (16) based upon an effect size of 1.23, a power of 0.99 and type 1 error or alpha level of 0.05.

The investigation was approved by the institutional ethics review board, and all subjects were informed of the benefits and risks of the investigation prior to signing an institutionally approved consent form to participate in the study. Subjects were familiar with the IMTP protocol and had  $\geq 6$  months resistance training experience of the power clean and its' derivatives; all IMTP trials were assessed by certified strength and conditioning specialists. At the time of testing subjects were mid-season in the first week of a power mesocycle having performed a four-week maximum strength mesocycle.



## Procedures

All testing took place at the same time of day and a subgroup (n=10) returned on a second occasion seven days later at the same time of day to minimize the effect of circadian rhythm and to determine between-session reliability. Subjects were required to abstain from training for 48 h before testing and asked to maintain a consistent fluid and dietary intake on each day of testing.

### Pre-isometric assessment warm up

All subjects performed a standardized warm up comprised of ten body weight squats and lunges followed by two isometric efforts at a perceived intensity of 50, and 75% of maximum effort, interspersed with a one-minute rest period (5, 29).

### Isometric mid-thigh pull protocol

The IMTP testing was performed on a portable force plate sampling at 1000 Hz (Kistler, Winterthur, Switzerland, Model 9286AA, SN 1209740) using a portable IMTP rack (Fitness Technology, Adelaide, Australia. Sampling at 1000 Hz has been shown to produce high reliability for isometric force-time variables (12). A cold rolled steel bar was positioned to correspond to the athlete's second-pull power clean position where the bar height could be adjusted (3 cm increments) at various heights above the force plate to accommodate different sized athletes. Athletes were strapped to the bar in accordance to previous research (20) and positioned in two different postures; both postures required a standardised knee joint angle of 145° however required different hip joint angles of 145° (Hip<sub>145</sub>) and 175° (Hip<sub>175</sub>), respectively. Subjects were placed in position; knee and hip relative angles (angle between two segments) were measured with goniometry to ensure that the position was accurately reproduced during each trial, with the bar resting midway up the thigh (approximately

halfway between the iliac crest and the midpoint of the patella), just below the inguinal crease of the hip, to replicate the start position of the second pull phase of the clean. Hip<sub>145</sub> positioning resulted in a posture with shoulders directly above or slightly behind the bar, conversely Hip<sub>175</sub> resulted in a posture with shoulders noticeably behind the bar as illustrated in Figure 1.

All subjects received standardized instructions to pull as fast and as hard as possible and push their feet directly into the force plate until being told to stop, as these instructions have been shown to produce optimal results (7). Once the body was stabilised (verified by watching the subject and force trace) the IMTP was initiated with the countdown “3, 2, 1 pull,” with subjects ensuring that maximal effort was applied for five seconds. Ground reaction force data were collected for a duration of eight seconds from the portable force platform which was interfaced with a laptop and recorded using Bioware software (Version 5.11; Kistler Instrument Corporation, Winterthur, Switzerland). Minimal pre-tension was allowed to ensure there was no slack in the body prior to initiation of pull and subjects were instructed to be as still as possible during the weighing period, without initiating a pull on the bar, until given the instructions to ‘pull’. Trials without a stable baseline force trace (change in force > 50 N) were rejected along with trials with a visible countermovements, subsequently another trial was performed (14, 31). Subjects performed a total of two maximal effort trials at each hip joint angle in a randomised and counterbalanced order, with each trial and interspersed with a 2-minute rest period. Strong verbal encouragement was given for all trials and subjects. In line with previous recommendations, if the difference between the two trials exceeded 250 N then a third trial was performed (4, 29). The mean of two trials were used for statistical analyses.

### Isometric force-time curve assessment

All force-time data recorded during the IMTP were inspected using a customized analysis Microsoft Excel spreadsheet (version 2016, Microsoft Corp., Redmond, WA, USA) to determine specific force-time characteristics. The maximum force generated during the five second maximum effort IMTP was reported as the absolute PF (22). Additionally, time-specific force values at 100 ms ( $\text{Force}_{100}$ ), 150 ms ( $\text{Force}_{150}$ ) and 200 ms ( $\text{Force}_{200}$ ) were calculated (12, 22). Net PF and net time-specific force values were calculated by subtracting BW (calculated during 1 second weighing period) from the time-specific force value. RFD at pre-determined time bands 0-100, 0-150 and 0-200 ms ( $\text{RFD}_{100}$ ,  $\text{RFD}_{150}$  and  $\text{RFD}_{200}$ ) were also calculated using the equation:  $\text{RFD} = \Delta\text{force} / \Delta\text{time interval}$  (4, 12, 22, 29). The onset of the contraction was determined when vertical ground-reaction force deviated 5 SD of BW (14). The combined residual force and BW were calculated as the average force over a 1 second stationary weighing period (in mid-thigh pull position posture) prior to the initiation of the IMTP (14).

### Statistical analyses

Statistical analyses were performed using SPSS software version 23 (SPSS, Chicago, Ill, USA). Normality for all variables was confirmed using a Shapiro Wilks-test. Within-session reliability and between-session reliability were assessed via intraclass correlation coefficients (ICC), 95% confidence intervals (CI), coefficient of variation (CV) calculated as  $\text{SD} / \text{mean} \times 100$  and standard error of measurement (SEM). Minimum acceptable reliability was determined with an ICC  $>0.7$  and CV  $<15\%$  (2, 22).

Paired sample t tests and effect sizes were used to compare IMTP kinetics between sessions. Differences in IMTP kinetics between postures were assessed using paired sample t tests, effect sizes, mean differences and percentage differences. Effect sizes were calculated using Hedges' *g* method (24) and interpreted using Hopkins' scale (25). The criterion for significance was set at  $p \leq 0.05$ .

## RESULTS

High within-session reliability was observed for hip<sub>145</sub> IMTP PF (ICC = 0.99, CV = 2.8%), time-specific force values (ICC = 0.92-0.98, CV = 3.5-6.2%), RFD at pre-determined time bands (ICC = 0.91-0.97, CV = 5.9-12.1%) and net forces (ICC = 0.91-0.98, CV = 4.6-11.6%); all achieving minimum acceptable reliability criteria (Table 1). With the exception of hip<sub>175</sub> RFD<sub>100</sub> and net force<sub>100</sub> which failed to meet minimum acceptable reliability criteria, high within-session reliability was observed for hip<sub>175</sub> IMTP PF (ICC = 0.99, CV = 2.8%), time specific force values (ICC = 0.93-0.98, CV = 2.9-5.8%), RFD at pre-determined time bands (ICC = 0.86-0.96, CV = 8.4-13.3%) and net forces (ICC = 0.83-0.97, CV = 5.3-13.7%) (Table 1). Body weight was highly reliable, irrespective of posture (ICC = 0.93-0.95, CV = 3.5-5.0%) (Table 1).

\*\*\*Insert Table 1 about here\*\*\*

Between-session testing demonstrated high reliability for all kinetics across both postures (ICC = 0.72-0.97, CV = 4.5-12.8%) with the exception of RFD<sub>100</sub> which failed to achieve minimum acceptable reliability criteria for both postures (Table 2). Significant differences

between sessions were observed only for hip<sub>145</sub> PF ( $p = 0.033$ ) and net PF ( $p = 0.05$ ) with effect sizes revealing a small difference ( $g = 0.21-0.23$ ). No other significant differences ( $p > 0.05$ ,  $g \leq 0.22$ ) were observed between sessions for all IMTP kinetics across both postures (Table 2).

\*\*\*Insert Table 2 about here\*\*\*

IMTP descriptive statistics between postures are presented in Table 3 along with  $p$  values, effect sizes, mean and percentage differences. Trivial non-significant differences were demonstrated between postures for PF and force<sub>100</sub> ( $p > 0.05$ ,  $g \leq 0.14$ ). However, hip<sub>145</sub> produced significantly greater time-specific force values ( $p \leq 0.025$ ,  $g = 0.25-0.28$ ), RFD at pre-determined time bands ( $p \leq 0.001$ ,  $g = 0.59-0.78$ ) and net forces ( $p \leq 0.001$ ,  $g = 0.57-0.74$ ) in comparison to hip<sub>175</sub>, with effect sizes indicating small to moderate differences (Table 3). Conversely, significantly higher BW ( $p < 0.001$ ) was observed with a hip<sub>175</sub> angle compared to hip<sub>145</sub>, with a moderate effect size ( $g = 0.74$ ) (Table 3).

\*\*\*Insert Table 3 about here\*\*\*

## DISCUSSION

The aims of the present study were to compare IMTP kinetics between commonly reported hip joint angles 145° and 175° with a standardized knee joint angle. This study is the first to compare a hip<sub>175</sub> joint angle to a hip<sub>145</sub> joint angle finding significantly greater time-specific force values, RFD at pre-determined time bands and net forces with a hip<sub>145</sub> posture compared to a more extended hip<sub>175</sub> posture (Table 3); in agreement with our hypotheses.

Equally, both postures resulted in high within-session and between-session reliability measures for all IMTP kinetics, with the exception of  $RFD_{100}$  which failed to meet minimum acceptable reliability for both postures between-sessions (Table 1 & 2). Consequently, the results from this study suggest a  $145^\circ$  hip angle is a more favourable position for rapid force production compared to a more extended hip position ( $175^\circ$ ) during IMTP testing. Therefore, practitioners should consider administering IMTP testing with an approximate  $145^\circ$  relative hip joint angle compared to a  $175^\circ$  hip joint angle, while also acknowledging that adopting different and inconsistent joint angles can significantly influence IMTP kinetics.

A diverse range of hip and knee joint angles have been reported within the literature for IMTP testing (1, 4, 22, 23, 38, 39, 42, 47). To our knowledge, Comfort et al. (8) and Beckham et al. (6) are the only studies to examine the effect of joint angle on a range of IMTP kinetics reporting conflicting findings. Comfort et al. (8) demonstrated no significant or meaningful differences ( $p > 0.05$ ,  $d \leq 0.061$ ) for PF, maximum RFD and impulse at 100-, 200- and 300 ms between joint angles and the authors advocated the use of a self-preferred mid-thigh pull position to minimise the learning effect. Conversely, Beckham et al. (6) found greater peak force and time-specific force values (small to large effect sizes) were achieved with a hip joint angle of  $145^\circ$  compared to a more flexed  $125^\circ$  angle. The present study compared a  $hip_{145}$  joint angle to an extended  $hip_{175}$  joint angle reporting no significant differences in PF between postures, but small to moderate significant differences in time specific-force values, RFD at pre-determined time bands and net forces were observed between postures (Table 3). Notably, greater mean and percentage differences were observed for net forces and RFD variables (Table 3) between postures indicating a greater influence on these kinetic variables. As such, the results from the present study are in agreement with Beckham et al. (6) highlighting that hip joint angle and subsequent body position influences isometric rapid force production. Supporting the recommendations of Beckham et al. (6) we

recommend coaches and researchers should consider administering an approximate 145° hip joint angle for IMTP testing.

The data from the present study shows that a hip<sub>145</sub> position appears to be a favourable position to assess the rapid force production capabilities of athletes while also demonstrating that hip joint angle directly influences time specific-force, net force and RFD characteristics (Table 3). This is supported by previous studies who have shown differences in maximum RFD and PF between 90° and 120° knee flexion during the isometric leg press (32). Beckham et al. (5) also observed significant differences in PF between various positions in the deadlift and the mid-thigh pull position. Interestingly, the authors compared a mid-thigh pull position to a deadlift lockout position demonstrating large differences in PF ( $d = 1.23$ ); however, PF was the only kinetic variable examined and the specific joint angles of the lockout position were not provided. Nonetheless, based on the results of this study and corroborative research, lower limb joint angle influences force production during isometric testing (5, 6, 32). As such, coaches and researchers should ensure joint angles are standardised and consistent between testing occasions to allow valid comparisons of performance variables when longitudinally monitoring neuromuscular performance, so such changes in IMTP kinetics can be attributed to training or fatigue, and not to differences in joint angles.

Coaches use the IMTP to assess the rapid force production properties of their athletes to monitor and inform future training, thus it is imperative that athletes adopt the most optimal and favourable position (joint angle) to rapidly produce force. The results of the present study demonstrate an extended hip joint angle of 175° was a suboptimal position for force production compared to hip<sub>145</sub> joint angle (Table 3), while Beckham et al. (6) observed a flexed 125° hip joint angle was also suboptimal in force production compared to hip<sub>145</sub>. Collectively, the results of these studies suggest that body position relative to the bar does matter for IMTP force production. Failure to place athletes in the optimal joint angles (body

position) of hip<sub>145</sub> could limit rapid force production, potentially leading to misinterpretations of their force production capabilities.

A stable baseline force during the weighing period with minimal pre-tension before the onset of a rapid contraction is recommended when conducting isometric testing (31). Interestingly, considerably greater BW (weighing period forces) was observed for the hip<sub>175</sub> posture compared to the hip<sub>145</sub> (Table 3). This indicates higher levels of pre-tension were achieved with the hip<sub>175</sub> posture which is suboptimal for evaluating RFD during isometric testing (31); and should therefore be avoided for IMTP testing.

Notably, significantly greater RFD at pre-determined time bands were demonstrated with a hip<sub>145</sub> posture compared to hip<sub>175</sub>, with mean percentage differences ranging from 16.8-21.1% (Table 3). As RFD was calculated as  $\Delta \text{force} / \Delta \text{time interval}$  the consistently greater RFD may be explained by several factors including, the significantly greater net forces and lower BW (weighing period forces), which has a direct effect on the change in force component of the RFD equation. Additionally, significantly greater force<sub>150</sub> and force<sub>200</sub> values were observed with a hip<sub>145</sub> joint angle, directly influencing RFD. Collectively the abovementioned factors such as lower BW (weighing period force to determine the onset of contraction – due to lower pre-tension), greater net forces and time-specific forces results in a greater change in force, thus greater RFD with a hip<sub>145</sub> joint angle. Thus, practitioners are recommended to administer IMTP testing with a hip<sub>145</sub> joint angle for a more favourable position to attain RFD, time-specific force values and net force data.

Numerous investigations have adopted hip joint angles of approximately 170-175° during IMTP testing (1, 4, 29, 42, 47); however, interpretation of these aforementioned studies may be limited, because the results of the present study indicate higher levels of pre-tension, lower RFD, lower time-specific forces, lower net forces, and lower reliability measures are



achieved with the hip<sub>175</sub> posture (Tables 1-3). This posture appears to be a suboptimal position for producing force and RFD compared to hip<sub>145</sub>, potentially due to differences in length tension relationship of the hip extensors and differences in moment arms (48). We suggest that the hip joint angles reported by the aforementioned studies (1, 4, 29, 42, 47) may be misrepresented and we question whether the authors are potentially referring absolute hip or trunk angle relative to a vertical straight line in comparison to measuring relative joint angle (angle between two segments meeting at a point) as done in the present study (19) (Figure 2). Figure 2 illustrates the notable differences in trunk position relative to the bar between absolute and relative hip<sub>175</sub> joint angles. Therefore, coaches and researchers are advised to specify and standardise their knee and hip joint angles adopted for IMTP testing and state whether absolute or relative joint angles were measured to avoid confusion and allow the replication of IMTP testing methodologies.

**\*\*Insert Figure 2 about here\*\***

The present study found PF to demonstrate the highest between-session reliability measures for both postures (Table 2) similar to the observations of previous between-session ( $ICC \geq 0.89$ ,  $CV \leq 4.6\%$ ) (8, 11, 15, 45) and within-session research ( $ICC \geq 0.97$ ,  $CV \leq 3.2\%$ ) (12, 22). Equally, both postures demonstrated high levels of within-session reliability for time-specific force values (Table 1) comparable to the reliability measures reported in previous research (4, 12, 22, 29). Limited studies have inspected the between-session reliability of time-specific force values (15, 26). High and acceptable between-session reliability measures were demonstrated for all time-specific force values (Table 2) in accordance with the reliability measures reported in youth male soccer players (15) and higher than the measures reported by James et al. (26). The results from this study confirm that both postures produce

equally high within-session and between-session reliability measures for PF and time-specific force values.

Haff et al. (22) has shown that the method to quantify RFD can influence the resultant value and reliability of such measures, and as such, using pre-determined time bands to calculate RFD has been recommended. To our knowledge only one other study (26) has assessed the between session reliability of RFD at pre-determined time bands.  $RFD_{100}$  in the present exceeded minimum acceptable reliability criteria at both postures (between-sessions) similar to the results of previous research (26). Conversely, lower and acceptable levels of variance were demonstrated for  $RFD_{150}$  and  $RFD_{200}$  consistent with the results of James et al. (26) who also showed improved RFD reliability measures over longer time intervals. High and acceptable within-session reliability measures were observed for all RFD variables during  $hip_{145}$  testing however  $RFD_{100}$  and  $net\ force_{100}$  exceeded minimum acceptable reliability at  $hip_{175}$  posture (Table 1). Therefore, the results from this study confirm that a  $hip_{145}$  posture produces high-within session reliability for all RFD variables however both postures result in unacceptable reliability for  $RFD_{100}$  (Table 1 & 2).

It should be acknowledged the present study only examined the effect of two different hip joint angles ( $145^\circ$  and  $175^\circ$ ) on IMTP kinetics, while Beckham et al. (6) only compared two hip joint angles ( $145^\circ$  and  $125^\circ$ ) as well. Comfort et al. (8) recommends the use of a self-preferred selection of knee and hip joint angles as reporting no significant differences between self-preferred position and a range of knee ( $120^\circ$ ,  $130^\circ$ ,  $140^\circ$ , and  $150^\circ$ ) and hip joint angles. The present study and Beckham et al. (6) both demonstrated greater force production with a  $hip_{145}$  but did not compare this to a self-preferred position. Therefore, further research is required comparing  $hip_{145}$  joint angle to self-preferred position to determine which body position results in optimal force production.

## PRACTICAL APPLICATIONS

Coaches and researchers should conduct IMTP testing with a 145° hip joint angle due to the greater IMTP kinetics and lower levels of pre-tension observed in this position compared to a 175° hip joint angle. As such, coaches and researchers should ensure that joint angles are standardised and kept consistent between testing occasions to allow valid comparisons of performance variables when longitudinally monitoring neuromuscular performance, so such changes in IMTP kinetics can be attributed to training or fatigue, and not to differences in joint angles. Furthermore, researchers are recommended when publishing research to report the knee and hip joint angles adopted for IMTP testing due to the effect on IMTP kinetics and reliability; while specifying if relative or absolute joint angles were measured.

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**Table 1. Within-session reliability measures of IMTP kinetics across postures**

	Variable	ICC	95% CI		CV (%)	95% CI		SEM
			LB	UB		LB	UB	
Hip <sub>145</sub>	PF	0.99	0.97	1.00	2.8	1.8	3.7	68.1
	Force <sub>100</sub>	0.92	0.82	0.96	6.2	4.5	7.8	92.5
	RFD <sub>100</sub>	0.91	0.82	0.96	12.1	8.9	15.3	768.6
	Force <sub>150</sub>	0.97	0.94	0.99	4.6	3.4	5.7	72.0
	RFD <sub>150</sub>	0.97	0.93	0.98	7.5	4.9	10.1	461.5
	Force <sub>200</sub>	0.98	0.95	0.99	3.5	2.3	4.6	67.8
	RFD <sub>200</sub>	0.95	0.90	0.98	5.9	3.5	8.2	394.6
	Net PF	0.98	0.95	0.99	4.6	3.2	6.1	87.1
	Net Force <sub>100</sub>	0.91	0.81	0.96	11.6	8.6	14.7	80.4
	Net Force <sub>150</sub>	0.97	0.93	0.99	7.5	5.2	9.8	67.9
	Net Force <sub>200</sub>	0.96	0.91	0.98	5.9	3.8	8.0	74.8
Hip <sub>175</sub>	BW	0.95	0.90	0.98	3.5	2.1	5.0	35.4
	PF	0.99	0.98	1.00	2.8	2.1	3.5	66.2
	Force <sub>100</sub>	0.93	0.82	0.97	5.8	4.1	7.4	78.7
	RFD <sub>100</sub>	0.86	0.69	0.93	18.1	10.7	25.5	778.4
	Force <sub>150</sub>	0.95	0.88	0.98	5.3	3.9	6.8	83.5
	RFD <sub>150</sub>	0.90	0.78	0.95	13.3	8.4	18.1	2004.3
	Force <sub>200</sub>	0.98	0.95	0.99	2.9	1.8	4.0	58.2
	RFD <sub>200</sub>	0.96	0.91	0.98	8.4	5.9	10.8	345.7
	Net PF	0.97	0.93	0.98	5.3	3.6	7.0	98.3
	Net Force <sub>100</sub>	0.83	0.64	0.92	18.5	11.7	25.4	86.0
	Net Force <sub>150</sub>	0.88	0.75	0.95	13.7	8.8	18.5	104.3
	Net Force <sub>200</sub>	0.95	0.89	0.98	7.5	4.8	10.2	75.1
	BW	0.93	0.85	0.97	5.0	3.1	7.0	53.2

Key: Hip<sub>145</sub>: Hip joint angle 145°; Hip<sub>175</sub>: Hip joint angle 175°; PF: Peak Force; RFD: Rate of force development; BW: Bodyweight; ICC: Intraclass Correlation Coefficient; CV: Coefficient of Variation; Force<sub>100</sub>: Force at 100 ms; Force<sub>150</sub>: Force at 150 ms; Force<sub>200</sub>: Force at 200 ms; RFD<sub>100</sub>: RFD 0-100 ms; RFD<sub>150</sub>: RFD 0-150 ms; RFD<sub>200</sub>: RFD 0-200 ms; CI: Confidence interval; LB: Lower Bound; UB: Upper bound; Standard error of measurement

**Table 2. Between-session reliability measures of IMTP kinetics across postures (n=10)**

	Variable	Session 1		Session 2		ICC	95% CI		CV (%)	95% CI		SEM	p	g
		Mean	SD	MEAN	SD		LB	UB		LB	UB			
Hip <sub>145</sub>	PF (N)	2656.1	628.2	2518.9	643.6	0.97	0.81	0.99	4.5	1.6	7.3	110.2	0.033	0.21
	Force <sub>100</sub> (N)	1370.3	280.0	1381.3	267.2	0.84	0.33	0.96	8.0	3.6	12.5	109.5	0.872	-0.04
	RFD <sub>100</sub> (N/s)	5548.4	2552.3	5729.5	1802.2	0.85	0.36	0.96	15.2	9.4	21.1	867.0	0.740	-0.08
	Force <sub>150</sub> (N)	1731.0	381.0	1690.8	394.3	0.90	0.61	0.98	7.6	3.5	11.7	121.4	0.608	0.10
	RFD <sub>150</sub> (N/s)	6103.3	2314.0	5882.6	2176.8	0.91	0.64	0.98	11.9	5.8	17.9	670.2	0.612	0.09
	Force <sub>200</sub> (N)	1960.3	425.0	1883.7	437.3	0.94	0.77	0.99	6.6	4.0	9.1	106.5	0.264	0.17
	RFD <sub>200</sub> (N/s)	5724.1	1868.7	5376.4	1837.4	0.94	0.77	0.99	9.4	5.6	13.1	457.7	0.235	0.18
	Net PF (N)	1883.5	577.5	1746.9	585.1	0.96	0.79	0.99	6.6	2.2	11.1	114.8	0.050	0.23
	Net Force <sub>100</sub> (N)	597.7	253.0	609.3	180.9	0.85	0.36	0.96	12.8	7.2	18.4	86.0	0.830	-0.05
	Net Force <sub>150</sub> (N)	958.3	344.1	918.8	325.3	0.91	0.65	0.98	9.9	4.5	15.2	100.5	0.542	0.11
	Net Force <sub>200</sub> (N)	1187.7	371.0	1111.7	366.1	0.94	0.76	0.99	9.7	6.3	13.1	91.8	0.191	0.20
BW (N)	772.6	121.6	772.0	143.9	0.97	0.86	0.99	4.0	2.5	5.4	24.5	0.970	0.00	
Hip <sub>175</sub>	PF (N)	2556.4	611.2	2531.8	574.6	0.97	0.89	0.99	5.3	3.0	7.6	101.0	0.716	0.04
	Force <sub>100</sub> (N)	1388.0	186.6	1339.7	262.4	0.88	0.55	0.97	5.2	0.1	10.3	78.5	0.33	0.20
	RFD <sub>100</sub> (N/s)	4484.1	1665.4	4247.9	1327.8	0.68	-0.36	0.92	14.8	3.0	26.5	849.3	0.632	0.15
	Force <sub>150</sub> (N)	1663.4	278.3	1593.2	339.0	0.93	0.73	0.98	5.1	0.7	9.5	82.1	0.175	0.22
	RFD <sub>150</sub> (N/s)	4825.7	1549.6	4521.9	1380.3	0.83	0.73	0.98	13.1	4.5	21.8	603.2	0.878	0.20
	Force <sub>200</sub> (N)	1913.4	375.7	1839.3	390.2	0.95	0.80	0.99	5.3	1.7	9.0	86.5	0.181	0.19
	RFD <sub>200</sub> (N/s)	4869.4	1516.1	4621.9	1363.8	0.89	0.59	0.97	12.8	5.7	19.9	471.7	0.141	0.16
	Net PF (N)	1660.46	551.72	1655.81	476.37	0.95	0.80	0.99	9.5	4.3	14.7	112.9	0.951	0.01
	Net Force <sub>100</sub> (N)	492.04	169.37	463.72	142.11	0.72	-0.15	0.93	11.6	0.9	22.4	82.4	0.561	0.17
	Net Force <sub>150</sub> (N)	767.48	236.99	717.21	212.07	0.85	0.43	0.96	11.0	3.0	19.0	87.4	0.355	0.21
	Net Force <sub>200</sub> (N)	1017.52	307.14	963.32	275.49	0.89	0.608	0.974	11.9	5.7	18.0	93.6	0.364	0.18
BW (N)	895.9	167.5	876.0	158.6	0.97	0.88	0.99	3.2	1.2	5.3	29.6	0.3	0.12	

Key: Hip<sub>145</sub>: Hip joint angle 145°; Hip<sub>175</sub>: Hip joint angle 175°; PF: Peak Force; RFD: Rate of force development; BW: Bodyweight; ICC: Intraclass Correlation Coefficient; CV: Coefficient of Variation; Force<sub>100</sub>: Force at 100 ms; Force<sub>150</sub>: Force at 150 ms; Force<sub>200</sub>: Force at 200 ms; RFD<sub>100</sub>: RFD 0-100 ms; RFD<sub>150</sub>: RFD 0-150 ms; RFD<sub>200</sub>: RFD 0-200 ms; CI: Confidence interval; LB: Lower Bound; UB: Upper bound; SEM: Standard error of measurement



**Table 3. Comparisons of IMTP kinetics between postures**

Variable	Hip <sub>145</sub>		Hip <sub>175</sub>		<i>p</i>	<i>g</i>	Descriptor	Mean Difference (SD)		% Difference (SD)	
	MEAN	SD	MEAN	SD							
<b>PF (N)</b>	2839.5	677.7	2747.2	627.3	0.066	0.14	Trivial	92.3	(255.4)	2.6	(8.9)
<b>Force<sub>100</sub> (N)</b>	1483.6	306.5	1488.2	284.9	0.893	-0.02	Trivial	-4.6	(179.0)	-1.3	(12.9)
<b>RFD<sub>100</sub> (N/s)</b>	6095.4	2516.5	4766.4	1908.0	0.001	0.59	Small	1329.0	(1821.0)	16.8	(30.2)
<b>Force<sub>150</sub> (N)</b>	1900.8	416.4	1792.3	357.9	0.025	0.28	Small	108.5	(241.4)	4.5	(13.1)
<b>RFD<sub>150</sub> (N/s)</b>	6844.5	2426.4	5204.7	1639.9	<0.001	0.78	Moderate	1639.9	(1710.1)	21.1	(24.5)
<b>Force<sub>200</sub> (N)</b>	2125.5	442.2	2017.5	398.0	0.022	0.25	Small	108.0	(234.2)	4.4	(10.9)
<b>RFD<sub>200</sub> (N/s)</b>	6257.0	1802.3	5029.4	1611.9	<0.001	0.71	Moderate	1227.5	(1318.2)	18.5	(20.7)
<b>Net PF (N)</b>	2018.7	581.8	1791.5	524.4	<0.001	0.40	Small	227.2	(298.4)	10.4	(14.8)
<b>Net Force<sub>100</sub> (N)</b>	662.9	255.2	532.6	192.9	0.001	0.57	Small	130.3	(189.3)	14.4	(30.6)
<b>Net Force<sub>150</sub> (N)</b>	1080.0	367.5	836.6	286.8	<0.001	0.73	Moderate	243.4	(263.5)	19.5	(24.0)
<b>Net Force<sub>200</sub> (N)</b>	1304.7	367.3	1061.8	320.8	<0.001	0.69	Moderate	242.9	(265.7)	17.3	(19.4)
<b>BW (N)</b>	820.8	157.7	955.7	201.3	<0.001	-0.74	Moderate	-134.9	(71.5)	-16.2	(8.0)

Key: Hip<sub>145</sub>: Hip joint angle 145°; Hip<sub>175</sub>: Hip joint angle 175°; PF: Peak Force; RFD: Rate of force development; BW: Bodyweight; Force<sub>100</sub>: Force at 100 ms; Force<sub>150</sub>: Force at 150 ms; Force<sub>200</sub>: Force at 200 ms; RFD<sub>100</sub>: RFD 0-100 ms; RFD<sub>150</sub>: RFD 0-150 ms; RFD<sub>200</sub>: RFD 0-200 ms;

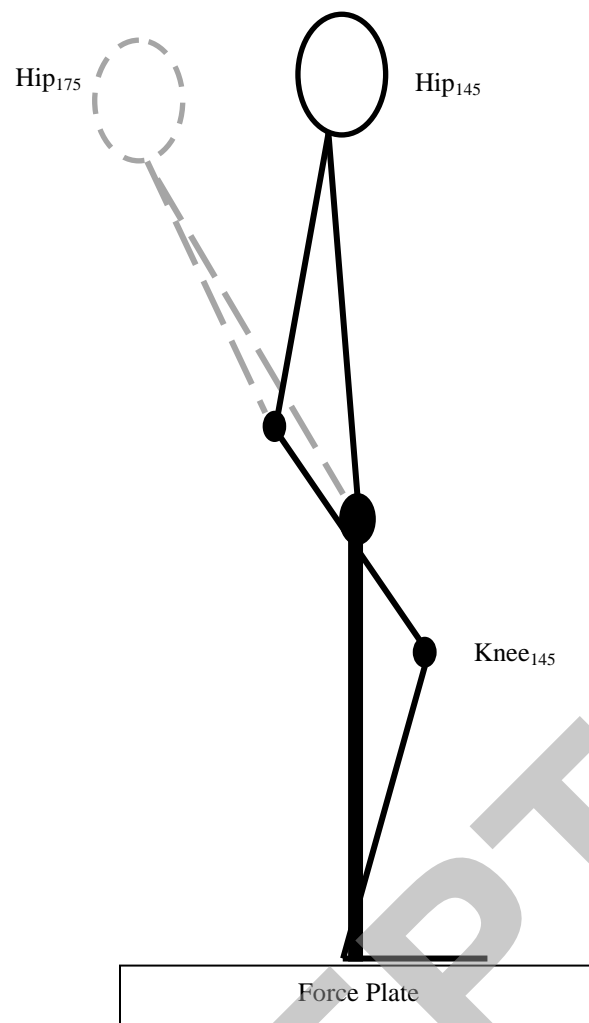


Figure 1. Schematic representation of IMTP positions with a standardised relative knee joint angle - Hip<sub>145</sub> (solid black line) and Hip<sub>175</sub> (dashed grey line).

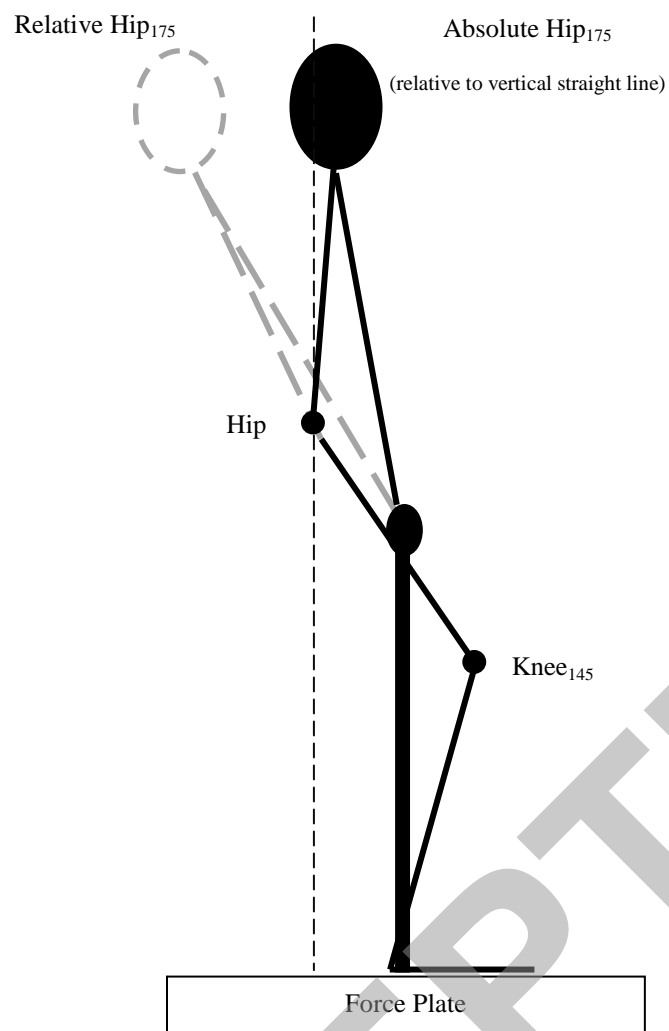


Figure 2. Schematic representation of relative and absolute 175° hip joint angles IMTP positions with a standardised relative knee joint angle – Absolute (trunk) hip<sub>175</sub> (solid black line) and Relative hip<sub>175</sub> (dashed grey line).